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Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete

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SP 114-10

Improvements in the Properties of Concrete Utilizing "Classified Fly Ash"

by K. Ukita, S. Shigematsu, and M. Ishii

Synopsis: Fly ashes having maximum particle diameters of 20,10 and 5μm, called "CLASSIFIED FLY ASH" (CFA) were investigated for their effect on concrete properties.

The CFA-concrete containing 15-30% CFA by cement weight requires less water content per unit volume. Greater strength and watertightness, lower drying shrinkage and higher resistance to alkali silica reaction are imparted to concrete by the addition of CFA. Grading or type of fly ash determines its effect on concrete.

Keywords: abrasion resistance; alkali-aggregate reactions; compressive strength; drying shrinkage; fly ash; permeability; water content

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Shun-ichi Shigematsu is Senior Research Engineer of Civil Engineering Dept., Shikoku Research Institute. He is Registered Consulting Engineer. He has been studying the effective use of coal ash especially in concrete and the durability of concrete.

Mitsuhiro Ishii is Assistant Senior Research Engineer of Civil Engineering Dept., Shikoku Research Institute. He has been studying the use of fly ash in concrete, alkali silica reaction.

INTRODUCTION

Despite increase in fly ash supply it is mostly used either as a raw material in cement production or disposed of at sites or for land reclamation. Utilization of fly ash as a concrete admixture is not very common.

The fly ash produced in recent years is of lower quality for use as a concrete admixture, because of changes in the combustion system of power plants and use of more diversified brands of coal (1).

The "classified fly ash", is produced by separating the fine components of fly ash by means of air classification. As this fly ash is made of fine particles of micron size and is of spherical shape, it was of interest to evaluate its effect in concrete (2). Three classes of fly ash were investigated.

EXPERIMENTAL

Materials

Fly Ash The classes of fly ash (represented by symbols) used and the methods by which they have been produced are described below.

Class

UFA: This is a product meeting JIS A [illegible] Standard, and is collected from electrostatic precipitator (EP) and marketed in bags [illegible] 30kg units).

CFA20: Products selectivity classified and collected from rear columns (second and third columns) of EP.

CFA10: The un[...] classified by [...] particle diame[...]
CFA5: The und[...] by air having [...]
The typical pr[...] components of [...] and the surfac[...] particle size [...]

Cement Normal[...] physical properties[...] 2.

Fine Aggregate[...] which was of same [...] was used. Its ph[...] Table 3. In the [...] andesite, which is [...] in Japan, was used [...]

Coarse Aggreg[...] The physical prope[...]

Mixing Water[...]

Properties and Tes[...]
Properties te[...] in Table 5.

Concrete Mixing
Common concre[...] under the mixing c[...] details are given [...]
The propertie[...] are given in Table [...]

D[...]

Fresh Concrete
Slump
The results c[...]
The slump is [...] other words, the a[...] when fly ash is us[...] slump as in the re[...] was more pronounce[...] ash (CFA20).
Air Content
The results f[...] Fig. 4.
Although no s[...] the air content is [...] having fine partic[...]

CFA10: The under sieve components of UFA were classified by air classifier having a maximum particle diameter of 10μm.
CFA5: The under sieve components of UFA obtained by air having a maximum particle diameter of 5μm.
The typical properties as well as chemical components of these products are given in Table 1 and the surface characteristics in Fig. 1, and particle size distribution in Fig. 2.

Cement Normal portland cement was used. The physical properties of cement are given in Table 2.

Fine Aggregate The sand from crushed sandstone, which was of same origin as the coarse aggregate, was used. Its physical properties are given in Table 3. In the alkali-silica reaction test, the andesite, which is regarded as a harmful aggregate in Japan, was used.

Coarse Aggregate Crushed sandstone was used. The physical properties are given in Table 4.

Mixing Water The portable city water was used.

Properties and Test Methods

Properties tested and methods used are given in Table 5.

Concrete Mixing

Common concrete mixture proportions were used, under the mixing conditions given in Table 6. The details are given in Table 7.

The properties determined for various mixes are given in Table 7.

DISCUSSION OF RESULTS

Fresh Concrete

Slump

The results of slump test are presented in Fig.3.

The slump is higher when fly ash is used. In other words, the amount of added water can be reduced when fly ash is used to obtain the same value of slump as in the reference concrete. This effect was more pronounced with the coarser classified fly ash (CFA20).

Air Content

The results for air content are presented in Fig. 4.

Although no significant differences are observed the air content is decreased slightly when fly ash having fine particles is used.

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Bleeding

The results of bleeding test are presented in Fig. 5. The data is scattered and indications are bleeding decreases as larger amounts of fine particle fly ash are used.

This tendency means that the segregation of concrete materials may be lower and the water retentivity could be enhanced. Such improvements in concrete characteristics may contribute to enhanced workability in the pumping of concreting.

Temperature Rise

The concrete containing fly ash shows a smaller temperature rise with respect to the reference concrete (Fig. 6).

The temperature rise is larger for mixes containing fly ash having finer particles. This may be due to the fine fly ash particles filling the space between cement particles (3), and accelerating the hydration of cement particles.

Hardened Concrete

Compressive Strength

The results of compressive strength test are presented in Fig. 7.

No distinctive differences between the effects of fly ashes are observed although there is a tendency for concrete containing finer fly ashes promoting the development of higher comprehensive strength. At any age concrete containing 15% fly ash yields strength equivalent to that of plain concrete.

At late ages (91 days), the strength is increased significantly for concrete with finer fly ash particles; strength equivalent to plain concrete can be obtained with fly ash content as high as 30%.

A more compacted structure and accelerated hydration of cement in the presence of fine classified fly ash particles explain most of the observations.

Water Permeability

The results of tests conducted on concrete cured for 28 or 91 days are presented in Fig. 8.

For the samples cured for 28 days, the water permeability was lower for concrete with finer particles and containing 15% fly ash. Sample having a fly ash content of 30%, shows higher permeability than that of the reference concrete. The pozzolanic action may be responsible for the different permeability values.

It can be concluded that the water-tightness of concrete can be increased when classified fly ash is used in place of un-classified fly ash. Water-tightness value depends on proportion and particle size of fly ash.

Abrasion Resist

The resistance samples cured for 2[illegible] Fig. 9.

At the fly ash resistance increase[illegible] The abrasion resista[illegible] ash containing fine[illegible] reference concrete. resistance was reduc[illegible] At a fly ash content is lower than that [illegible] resistance increase[illegible]

Drying Shrinkag

The results fo[illegible] Fig. 10.

At a fly ash c[illegible] shrinkage tends to [illegible] finer fly ash. The that of the plain c[illegible]

Samples with f[illegible] shrinkage.

Shrinkage valu[illegible] fly ash concrete sa[illegible] all fly ash concret[illegible] at a constant worka[illegible] water cement ratio.

Relation between Co[illegible] Properties

Relation betwe[illegible] Permeability

The relation b[illegible] and permeated depth

It can be seen of concrete increas[illegible] increases. The wat[illegible] age of concrete.

Relation betwe[illegible] Abrasion Resistance

The relation b[illegible] compressive strengt[illegible]

It can be seen resistance of concr[illegible] has a relatively st[illegible] strength, the value in strength.

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Abrasion Resistance

The resistance to abrasion conducted on concrete samples cured for 28 days or 91 days is given in Fig. 9.

At the fly ash proportion of 15%, the abrasion resistance increases with the fineness of fly ash. The abrasion resistance of the sample with CFA5 fly ash containing finest particles is higher than the reference concrete. In other cases, the abrasion resistance was reduced by several percent to 20%. At a fly ash content of 30%, the abrasion resistance is lower than that of the reference, although the resistance increases with fineness of fly ash.

Drying Shrinkage

The results for 91 days samples are given in Fig. 10.

At a fly ash content of 15%, the amount of drying shrinkage tends to be lower with samples containing finer fly ash. The shrinkage is equal or lower than that of the plain concrete.

Samples with fly ash content of 30%, show higher shrinkage.

Shrinkage values would have been lower in all fly ash concrete samples if they had been lower in all fly ash concrete samples if they had been made at a constant workability instead of at a constant water-cement ratio.

Relation between Compressive Strength and Other Properties

Relation between Compressive Strength and Water Permeability

The relation between comprehensive strength and permeated depth is illustrated in Fig. 11.

It can be seen in the figure that watertightness of concrete increases as the compressive strength increases. The water-tightness enhances with the age of concrete.

Relation between Compressive Strength and Abrasion Resistance

The relation between the abrasion values and compressive strength is illustrated in Fig. 12.

It can be seen in the figure that the abrasion resistance of concrete containing classified fly ash has a relatively strong correlation with compressive strength, the values decreasing with the increases in strength.

Relation between Compressive Strength and Drying Shrinkage

The relation between the shrinkage of 91 days concrete and the compressive strength (at 7 days) is illustrated in Fig. 13.

It can be seen in the figure that there is no correlation between drying shrinkage and compressive strength. The drying shrinkage seems to correlate better with the aggregate volume in concrete (4).

Effect of Particle Size on Compressive Strength

It is difficult to quantify the particle sizes of solid components in concrete, as they change with time of hydration and pozzolanic reaction. For this reason, the particle size of all solid components just before mixing (arbitrarily called the initial composite particle size) was taken into consideration.

The relationship between the equivalent specific surface area (calculated from the initial composite particle size distribution) and compressive strength is illustrated in Fig. 14. The calculations are described below:

Equivalent specific surface area denoted by As (cm^2/g) can be obtained from the following equation.

$$As = [(6/\rho).\Sigma(Xi/di)]/100$$

where, Σ represents the summation from lower to upper limit with respect to the 'i'-th particle size.

ρ is the equivalent specific weight of composite material, which can be expressed by the following equation:

$$\rho = [C + F + S + G]/[C/\rho c + F/\rho f + S/\rho s + G/\rho g]$$

C,ρc : Cement content and specific weight

S,ρs : Fine aggregate content and specific weight (dry-surface)

G,ρg : Coarse aggregate content and specific weight (dry basis)

F,ρf : Fly ash content and specific weight

Xi : Percentage of materials with particle size between di and di+1

di : Particle size of 'i'-th class

Following conclusions can be drawn:

Higher compressive strength is obtained with larger equivalent specific surface area.

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When the fly ash content is 15%, the increase in long term concrete strength is pronounced as compared with short-term strength. It can be assumed that this tendency is caused not only by the particle size, but also by the pozzolanic reaction of classified fly ash. In these calculations it is important to consider the particle size distribution of concrete materials as well as the water: cement ratio (or the amount of hydrating materials).

Effects on Alkali-Silica Reaction

Mortar tests were conducted by using andesite (ASTM C289 test results given in Fig. 15) that is known to be a typical harmful aggregate in Japan. The alkali content of cement (R_2O) was 1.2% and fly ash was mixed at an amount of 15% (30% in one test). Results of Fig. 16 indicate the following:

Alkali silica reaction is greatly suppressed by fly ash. Finer particle size is even more effective. Larger amounts of fly ash also inhibit this reaction. It should be recognized that the reaction may be accelerated by 'pessimum amount', depending on the kind and proportion of fly ash (5).

CONCLUSION

Incorporation of fly ash affects the properties of concrete significantly. The water content per unit volume of normal concrete is reduced when classified fly ash is used. Air content is not affected but concrete becomes more compacted. Bleeding is reduced and the rate of reaction is increased by fly ash. The compressive strength is increased at 91 days with finer particles of fly ash. Using 15% fly ash water tightness can be increased. Abrasion resistance is increased with finer particle size at a fly ash content of 15%. At earlier ages the shrinkage of fly ash concrete is lower than the reference but at later ages the value are equal or higher. All properties, except shrinkage can be correlated with the compressive strength. The particle size of solids in concrete in addition to the water-cement or water-binder ratio influences the strength of concrete. The inhibitive action of classified fly ash on alkali silica reaction is more pronounced than the unclassified fly ash.

In conclusion, we have identified the quality improvement effects of classified fly ash mixed in concrete, such as reduction of unit water content, enhancement of strength and water-tightness, and suppression of alkali silica reaction.

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TABLE 1--PHYSICAL PROPERTIES AND CHEMICAL COMPOSITIONS OF FLY ASH

Type of Fly Ash	Physical Properties			Chemical Compositions (%) *								
	Specific Gravity	Surface Area, Blaine	Mean Particle Size	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Ig.loss

TABLE 1--PHYSICAL PROPERTIES AND CHEMICAL COMPOSITIONS OF FLY ASH

Type of Fly Ash	Physical Properties			Chemical Compositions (%)*								
	Specific Gravity	Surface Area, Blaine (cm²/g)	Mean Particle Size (μm)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Ig.loss
UFA	2.28	3550	17.6	54.6	28.3	6.55	3.97	1.36	1.08	0.92	0.59	2.78
CFA20	2.31	5500	7.5	52.5	30.5	5.77	2.75	1.05	1.07	0.89	0.71	4.37
CFA10	2.46	8450	3.3	53.4	31.6	4.08	2.21	1.01	1.13	0.95	0.84	4.51
CFA5	2.51	12400	2.2	53.8	29.5	4.52	2.03	0.93	0.99	0.81	1.24	5.54

*Analysis Method: JIS M 8815

TABLE 2--PHYSICAL PROPERTIES OF CEMENT

Type	Specific Gravity	Surface Area(cm²/g)
Normal portland	3.16	3150

TABLE 3--PHYSICAL PROPERTIES OF FINE AGGREGATE

Type	Maximum size (mm)	Specific Gravity	Water absorption (%)	Grading Distribution mm (retained %)						Fineness modulus
				5	2.5	1.2	0.6	0.3	0.15	
Crushed Sand	5	2.58	1.31	0	9	28	49	70	90	2.46

TABLE 4--PHYSICAL PROPERTIES OF COARSE AGGREGATE

Type	Maximum size (mm)	Specific Gravity	Water absorption (%)	Grading Distribution mm (retained %)				Fineness modulus
				20	10	5	2.5	
Crushed Stone	20	2.60	1.24	2	57	96	99	6.54

TABLE 5--PROPERTIES AND TEST METHODS

	Properties	Test Methods	Note
Fresh	Slump	JIS A 1101	
	Air	JIS A 1128	

	(mm)		(%)					
Crushed Stone	20	2.60	1.24	2	57	96	99	6.51

TABLE 5--PROPERTIES AND TEST METHODS

	Properties	Test Methods	Note
Fresh Concrete	Slump	JIS A 1101	
	Air	JIS A 1128	
	Bleeding	JIS A 1123	
	Rise in Temperature	Simple method	
Hardened Concrete	Comp. Strength	JIS A 1108	
	Abrasion Resistance	Simple method	
	Water Permeability	Input method	Permeated Depth
	Drying Shrinkage	JIS A 1129	
Mortar	Alkali-Silica Reactivity	JIS A 5308	

TABLE 6--MIX CONDITION FOR CONCRETE

Water Binder ratio (W / B) (%)	Sand-Aggregate ratio (s / a) (%)	Unit Weight (kg/m³)		Note
		Binder* (B)	Water (W)	
0.55	0.45	340	187	* Binder(B) =Cement(C)+Fly Ash(F) Concrete:Non-AE Concrete

TABLE 7--CONCRETE MIXTURE PROPORTIONS

No.	Mix Type	Type of F.A.	F/(C+F) (%)	Gmax. (mm)	W/(C+F) (%)	s/a (%)	Unit Weight (kg/m³) Water (W)	Cement (C)	Fly Ash (FA)	F.Aggre. (S)	C.Aggre. (G)
1	Plain	-	0	20	55	45	187	310	0	748	923
2	CFA15	CFA	15	20	55	45	187	289	51	743	913
3	CFA30	CFA	30	20	55	45	187	238	102	733	905
4	CFA2015	CFA20	15	20	55	45	187	289	51	743	913
5	CFA2030	CFA20	30	20	55	45	187	238	102	735	905
6	CFA1015	CFA10	15	20	55	45	187	289	51	743	915
7	CFA1030	CFA10	30	20	55	45	187	238	102	738	910
8	CFA 5 15	CFA5	15	20	55	45	187	289	51	743	918
9	CFA 5 30	CFA5	30	20	55	45	187	238	102	738	905

TABLE 8--PROPERTIES DETERMINED

TABLE 8--PROPERTIES DETERMINED

No.	Mix Type	Type of F.A.	F/(C+F) (%)	Fresh Concrete: Slump	Fresh Concrete: Air	Fresh Concrete: Bleeding	Fresh Concrete: Rise in Temp.	Hardened Concrete: Comp. Strength	Hardened Concrete: Abrasion Resist.	Hardened Concrete: Water Permea.	Hardened Concrete: Drying Shrink.	Mortar: Alkali-Silica Reactivity
1	Plain	—	0	O	O	O	O	O	O	O	O	O
2	UFA15	UFA	15	O	O	O	—	O	O	O	O	O
3	UFA30	UFA	30	O	O	O	O	O	O	O	[illegible]	—
4	CFA2015	CFA20	15	O	O	O	—	O	O	O	O	O
5	CFA2030	CFA20	30	O	O	O	O	O	O	O	O	O
6	CFA1015	CFA10	15	O	O	O	—	O	O	O	O	—
7	CFA1030	CFA10	30	O	O	O	O	O	O	O	O	O
8	CFA 5 15	CFA 5	15	O	O	O	—	O	O	O	O	—
9	CFA 5 30	CFA 5	30	O	O	O	O	O	O	O	O	—

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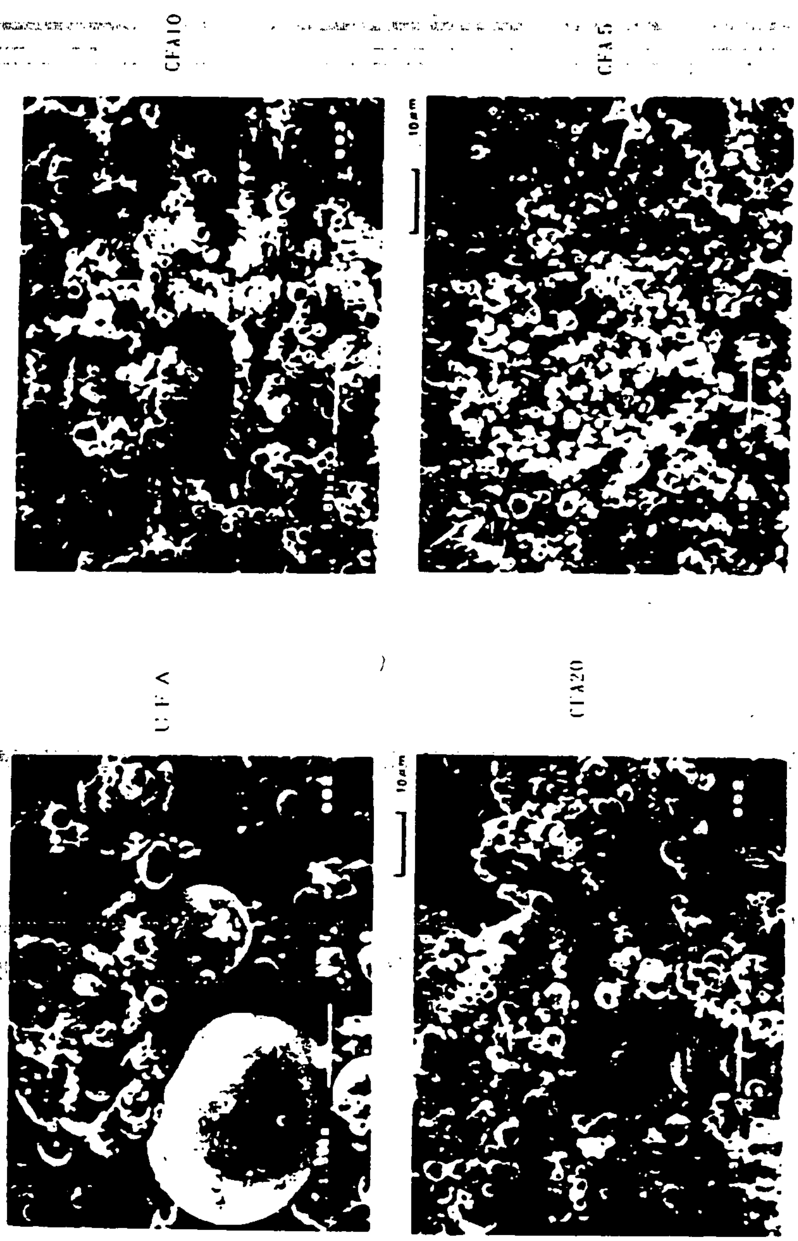


Fig. 1--Surface characteristics of fly ashes

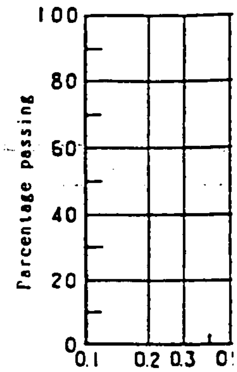
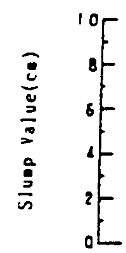


Fig. 2--Part



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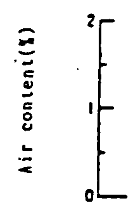

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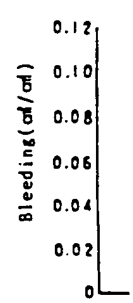

Fig. 5

Fig. 1--Surface characteristics of fly ashes

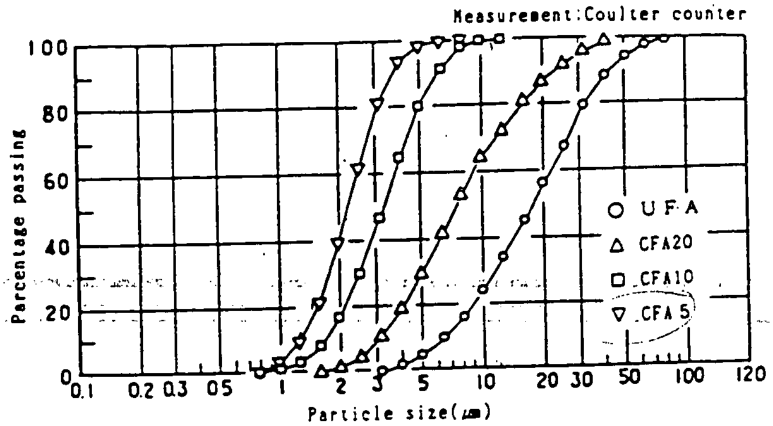

Fig. 2--Particle size distribution of fly ashes

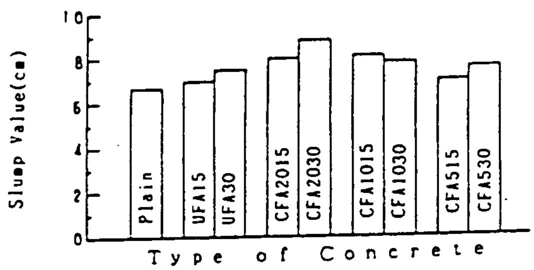

Fig. 3--Results of slump test

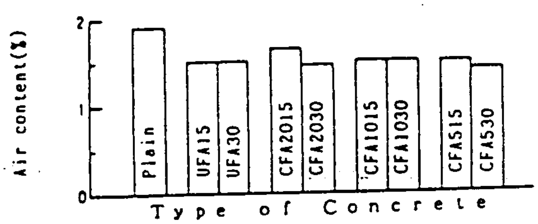

Fig. 4--Results of air test

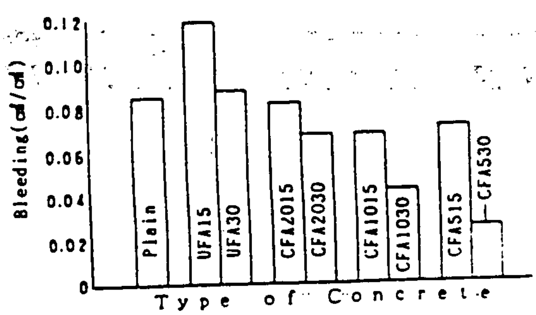

Fig. 5--Results of bleeding test

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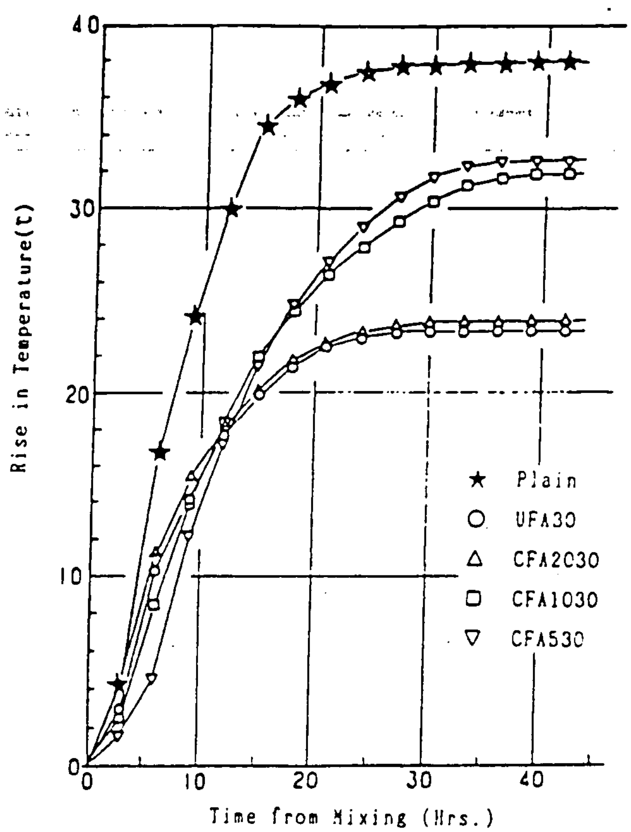

Fig. 6--Results of rise in temperature

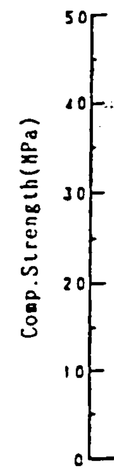

Fig. 7--

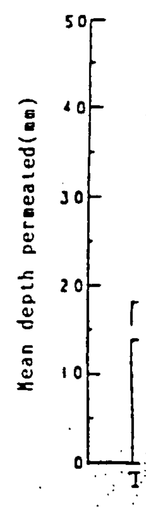

Fig. 8--

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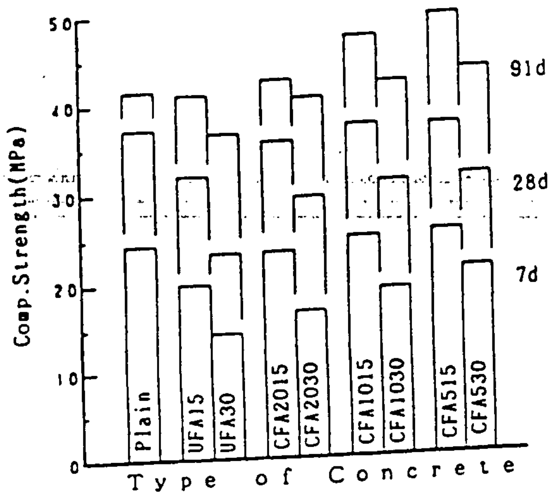


Fig. 7--Results of compressive strength

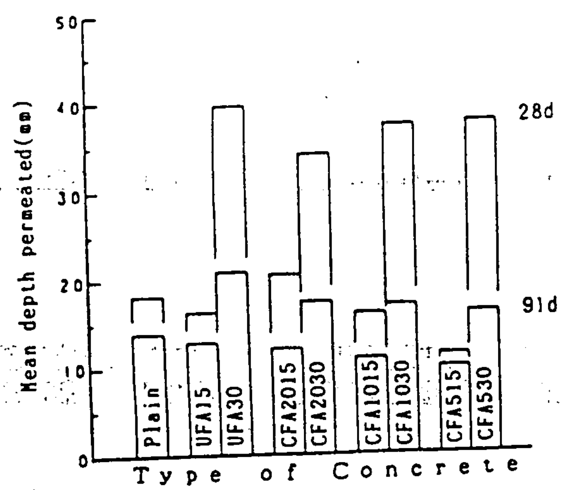


Fig. 8--Results of water permeability

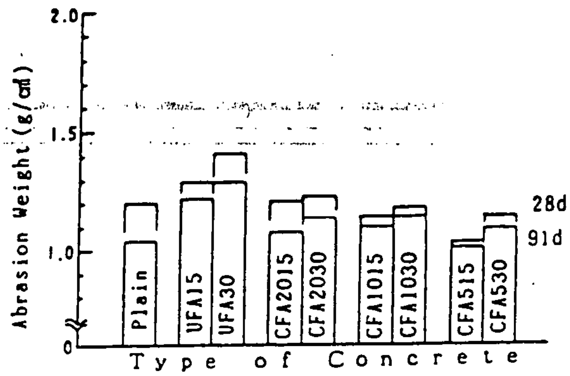


FIg. 9--Results of abrasion

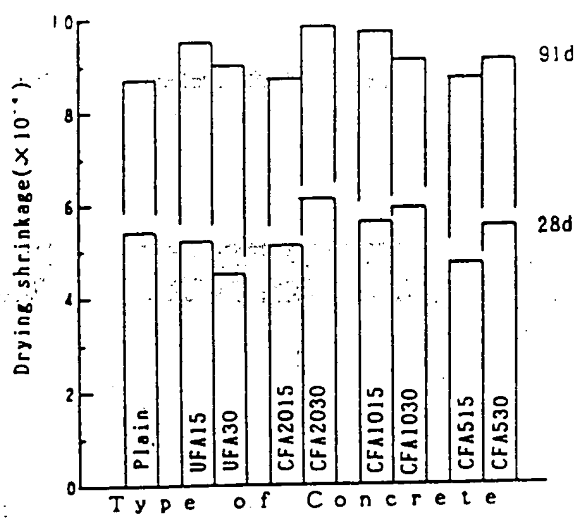
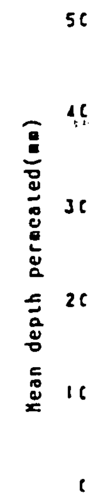


Fig. 10--Results of drying shrinkage



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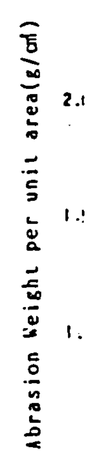

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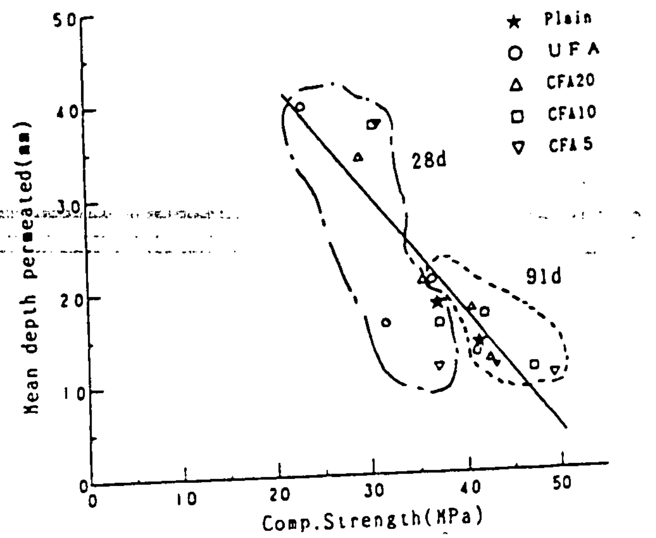

Fig. 11--Relation between mean depth permeated and compressive strength

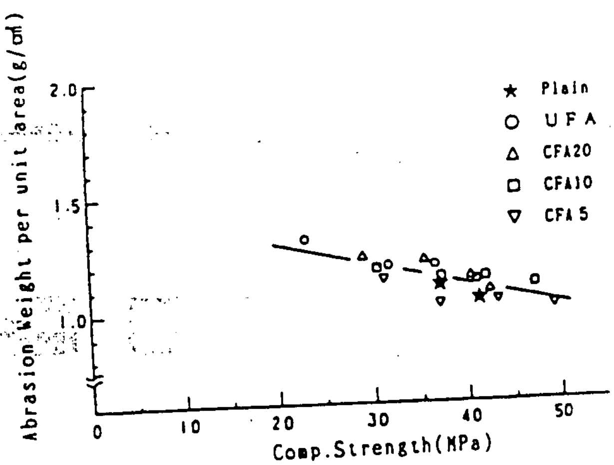

Fig. 12--Relation between abrasion weight per unit area and compressive strength

715-1-060 CIP
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GROUP ART UNIT: 1755

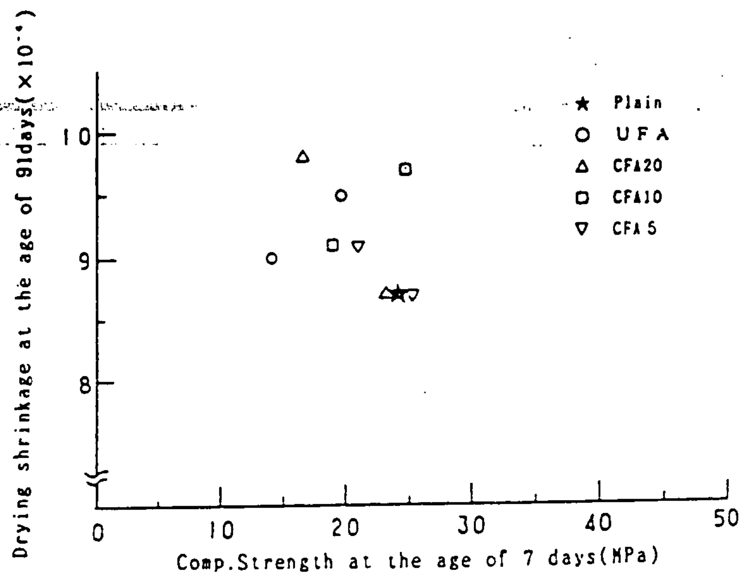

Fig. 13--Relation between drying shrinkage and compressive strength

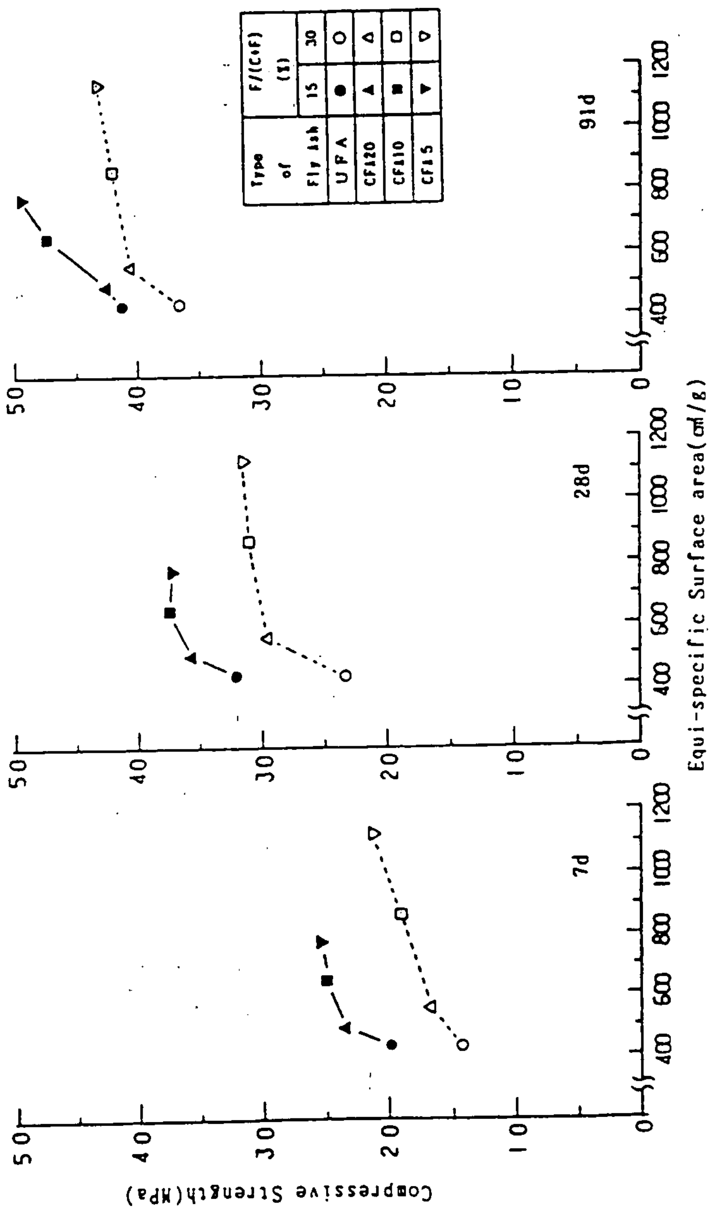

Fig. 14--Relationship between compressive strength and equi-specific surface area of all solid material in concrete

715-1-060 CIP
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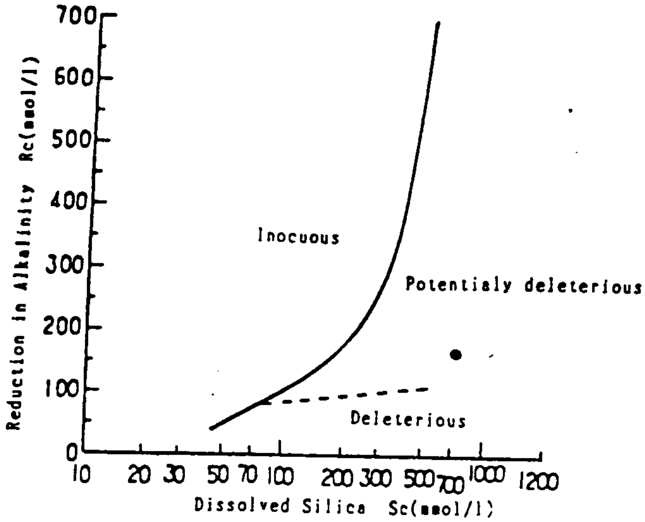

Fig. 15--Alkali silica reactivity of aggregate used (according to ASTM C289)

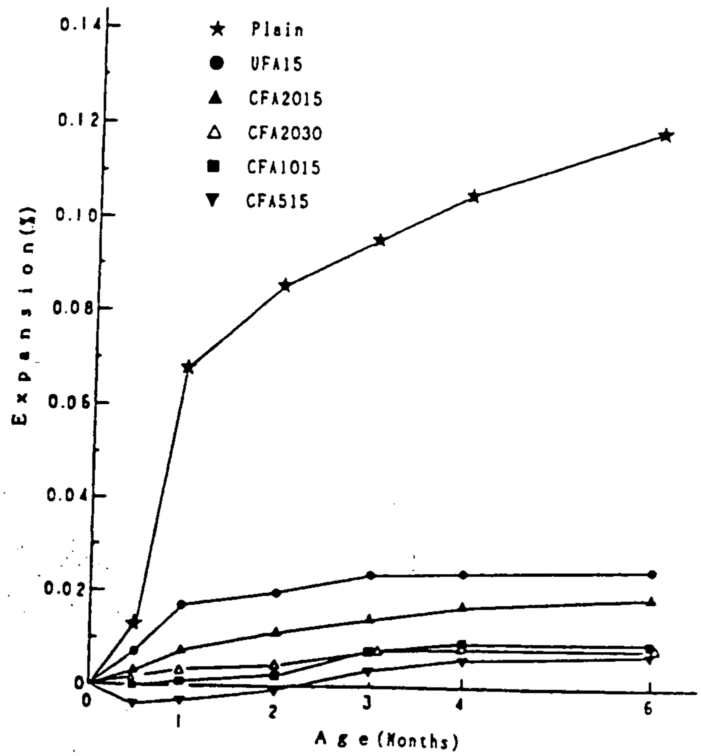

Fig. 16--Results of alkali silica reactivity test for mortar

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Synopsis: A study
fly ash from Lingar
high-efficiency air
grades with nomina
-45 μm fraction fro
improve the quality
of spherical particles
The raw fly as
with the requiremer
improved pozzolani
alkali-aggregate reac
the -45 μm fraction c
strength at 28d. This
beneficiation of the a
improved strength de
The hydration
at w/c=0.5 and curin
substitution increase
major ions in pore so
control. Mechanism
curing age are discuss
general, the ash-contai
At 28d there wa
expected due to pozz
pozzolanic reactivity w
of increased C-S-H
characterization of the
in similar quantities to
products. At 28d, the
chemical reactivity of
nucleation sites for C-S
curing ages extended to
in these systems.
The pore structur
porosimetry and their
uniquely related to the p
pastes serve to close t
intrusion. Whether thi
(possibly as a result of
remains to be establishec

Keywords: alkalie
ash; hydration; mi
permeability; poro